NAVAL RESEARCH LABORATORY

# NAVAL CENTER FOR SPACE TECHNOLOGY

Full-Sky Astrometric Mapping Explorer (FAME)
Detailed Science Requirements Document (SRD)

**NCST-D-FM001** **27 June 2001**



**4555 Overlook Avenue, S.W.**
**Washington, D.C. 20375-5000**

## RECORD OF CHANGES

| REVISION LETTER | DATE | TITLE OR BRIEF DESCRIPTION | ENTERED BY |
|---|---|---|---|
| — | 27 June 2001 | Released per ERN FM008 | M. Ream |

## TABLE OF CONTENTS


| Section | Title | Page |
|---|---|---|
| **1.** | **SCOPE** | **1-1** |
| 1.1 | Identification | 1-1 |
| 1.2 | Purpose | 1-1 |
| 1.3 | Mission Overview | 1-1 |
| 1.4 | Document Overview | 1-1 |
| **2.** | **REQUIREMENTS** | **2-1** |
| 2.1 | Performance Specifications | 2-1 |
| 2.2 | Scientific Objectives | 2-1 |
| 2.3 | Performance Requirements, Goals and Floor | 2-2 |
| 2.3.1 | Astrometry | 2-2 |
| 2.3.2 | Photometry | 2-4 |
| 2.3.2.1 | Passband Requirements – Astrometric and SDSS Filters | 2-4 |
| 2.3.2.2 | Passband Goals – Astrophysical Filters | 2-6 |
| **3.** | **FAME SUPPORTING NOTES** | **3-1** |
| 3.1 | Distance Scales | 3-1 |
| 3.1.1 | Cepheid Distances | 3-1 |
| 3.1.2 | RR Lyrae Distances | 3-2 |
| 3.1.2.1 | Parallaxes | 3-2 |
| 3.1.2.2 | Statistical Parallax | 3-2 |
| 3.1.3 | Subdwarf Distances | 3-2 |
| 3.1.4 | Open Clusters Distances | 3-2 |
| 3.1.4.1 | Open Cluster Memberships | 3-3 |
| 3.1.4.2 | Correlated Systematic Errors | 3-3 |
| 3.2 | Mass and Luminosity Calibration of Solar-Neighborhood Stars | 3-3 |
| 3.3 | Brown Dwarfs and Planets | 3-4 |
| 3.4 | Star-Forming Regions | 3-5 |
| 3.4.1 | Present Status | 3-5 |
| 3.4.2 | The Promise of FAME | 3-6 |
| 3.4.2.1 | Distances, Memberships, and Kinematics of Star-Forming Regions | 3-6 |
| 3.4.2.2 | Establishing the Zero-Point of Stellar Evolution | 3-6 |
| 3.4.2.2.1 | Ages | 3-6 |
| 3.4.2.2.2 | Masses | 3-6 |
| 3.4.2.3 | Evolution Towards the Main Sequence | 3-7 |
| 3.4.2.3.1 | Nearby Loose Associations | 3-7 |
| 3.4.2.3.2 | When Do Planets Form? | 3-7 |
| 3.4.3 | Surface Activity and Rotation | 3-7 |
| 3.4.4 | Photometric Binaries | 3-7 |
| 3.5 | Reference Frames | 3-8 |
| 3.6 | Stellar Astrophysics | 3-8 |
| 3.6.1 | White Dwarfs | 3-8 |
| 3.6.2 | Planetary Nebulae | 3-9 |
| 3.6.3 | Subdwarf O and B Stars | 3-9 |
| 3.6.4 | Horizontal-Branch Stars | 3-9 |
| 3.7 | Galactic Structure and Evolution | 3-9 |
| 3.7.1 | Dark Matter | 3-9 |
| 3.7.1.1 | Dwarf Stars | 3-9 |
| 3.7.1.2 | K Giants | 3-10 |
| 3.7.2 | Age of the Disk and Halo | 3-10 |

3.7.2.1 Age of the Disk ........ 3-10
3.7.2.2 Age of the Halo ........ 3-10
3.7.3 Distances to Interstellar Clouds ........ 3-11
3.7.3.1 Technique ........ 3-11
3.7.3.2 Radiation Field of Particular Interstellar Clouds ........ 3-11
3.7.3.3 Molecular Hydrogen ........ 3-11
3.7.3.4 Constituents of Interstellar Clouds ........ 3-12
3.7.3.5 Stars Inside Interstellar Clouds ........ 3-12
3.7.3.6 Masses and Densities ........ 3-12
3.7.4 Distances to Detached Eclipsing Binaries ........ 3-12
3.7.5 Galactic Kinematics ........ 3-13
3.7.6 Galactic Evolution ........ 3-13
3.8 Relativity ........ 3-13
3.9 Solar System ........ 3-13
3.10 Photometry ........ 3-14
3.10.1 Statistical Parallax of RR Lyraes ........ 3-14
3.10.2 Subdwarf Distance Scale ........ 3-14
3.10.3 Standard Candles ........ 3-14
3.10.4 Brown Dwarfs and Planets ........ 3-15
3.10.5 Variability of Solar-type Stars ........ 3-15
3.10.6 Stellar Pulsation ........ 3-15
3.11 References ........ 3-16
3.12 Definitions ........ 3-17

## LIST OF TABLES


| Number | Title | Page |
|---|---|---|
| Table 2-1. | FAME Astrometric Positions and Residuals - Performance Requirements, Goals and Floor for the 2½-year Mission | 2-2 |
| Table 2-2. | FAME Astrometric Proper Motions - Performance Requirements, Goals and Floor for the 2½-Year Mission | 2-3 |
| Table 2-3. | FAME Astrometric Parallaxes - Performance Requirements, Goals and Floor for the 2½ Year Mission | 2-4 |
| Table 2-4. | FAME Passband Requirements - Photometric Performance Requirements, Goals and Floor for the 2½ Year Mission | 2-5 |
| Table 2-5. | FAME Passband Goals - Filter Characteristics | 2-6 |

# 1. SCOPE

## 1.1 Identification

This document applies to the Full-Sky Astrometric Mapping Explorer (FAME) mission.

## 1.2 Purpose

This document establishes the scientific objectives for the FAME mission. These objectives are the basis for the detailed specifications for the performance of the FAME mission, which includes, but is not limited to the spacecraft bus, the instrument payload, the ascent support equipment, and related ground elements.

## 1.3 Mission Overview

The FAME mission will provide positions, proper motions, parallaxes, and photometry of 40 million stars, including nearly all stars between $5^{th}$ and 15th visual magnitude ($V$). The astrometric accuracies will be no worse than 50 microarcseconds (µas) at $V$=5 to 9 mag and 500 µas at $V$=15 mag. Stars will also be observed with the Sloan Digital Sky Survey (SDSS) g', r', i', and z' passbands for photometric magnitudes with millimagnitude (mmag) accuracies. To cover the entire sky the mission uses a scanning survey instrument, with a mission life of 2½ years and an extended mission to 5 years.

## 1.4 Document Overview

This Detailed Science Requirements Document (SRD) establishes the top-level scientific objectives for the FAME mission.

- Section 1.0, *Scope:* Purpose and contents of this document, and an overview of the FAME mission.
- Section 2.0, *Requirements:* The performance specifications and scientific objectives of the FAME mission, including requirements, goals, and floor categories.
- Section 3.0, *Supporting Notes:* Additional descriptions of the scientific objectives and performance specifications.

# 2. REQUIREMENTS

## 2.1 Performance Specifications

FAME will produce a star catalog based on a 2½-year mission with:

1. Positions, parallaxes, and proper motions of stars in the apparent visual magnitude range *V*=5 to 9 mag to an accuracy of 50 μas, 50 μas, and 70 μas/yr, respectively. At *V*=15 mag, the mission astrometric accuracy shall be no worse than 500 μas, 500 μas, and 500 μas/yr, respectively.
2. Photometric magnitudes for all stars in the astrometric band-pass, and also in the SDSS g', r', i', and z' band-passes. The precision of individual photometric observations will range from a few mmag at *V*=9 mag up to tens of mmag at *V*=15 mag. For constant stars the mission photometric accuracies will range from better than one mmag at *V*=9 mag to a few mmag at *V*=15 mag.
3. The above performance specifications apply to 90% of the sources at a given magnitude, with no more than a factor of two degradation in the performance for the other 10%. The sky coverage will exceed 98%, with an allowance of 2% for crowded regions. The stars to be observed will be included in an input catalog.

## 2.2 Scientific Objectives

FAME will provide:

1. Calibrations of the distances to "standard candles" such as the Galactic Cepheid variables and RR Lyrae stars that can be used to improve the distance and luminosity determinations to star clusters, nearby galaxies, and nearby clusters of galaxies.
2. Calibrations of the masses and luminosities of solar-neighborhood stars, including cluster members and field stars of both Population I and II, thus enabling diverse studies of stellar evolution and stellar astrophysics. In the case of Population II subdwarfs, this will allow the determination of the distances and ages of Galactic and extragalactic globular clusters with unprecedented accuracy. To achieve this objective it will be necessary to determine interstellar absorption and reddening with high accuracy.
3. Definitive determinations of the frequency of solar-type stars orbited by brown dwarf companions in the mass range of 10 to 80 Jupiter masses ($M_j$), with orbital periods up to somewhat longer than the duration of the mission. This will include an exploration of the transition region between giant planets and brown dwarfs, which appears to be in the range of 10 to 30 $M_j$.
4. Proper motions and distances for individual stars in star-forming regions and young clusters, for determinations of memberships, ages, and kinematics.
5. Studies of the structure and evolution of our Galaxy based on a sample of nearly 40 million stars within 2.5 kpc of the Sun, including an improved assessment of the amount and distribution of dark matter in the Galactic disk, and a better understanding of the formation and chemical evolution of our Galaxy based on analyses of the kinematics, chemical compositions, and ages of stars.

## 2.3 Performance Requirements, Goals and Floor

A performance requirement is the specification to which the instrument, spacecraft, and ground elements are designed. A goal is what is desired if this can be achieved within budget and schedule. The floor is the value beyond which the scientific justification is no longer compelling.

### 2.3.1 Astrometry

The FAME performance requirements, goals and floor for positions, proper motions, and parallaxes over the 2½-yr mission are listed in Tables 2-1, 2-2, and 2-3, respectively.

**Table 2-1. FAME Astrometric Positions and Residuals - Performance Requirements, Goals and Floor for the 2½-year Mission**

| | *V* (mag) | Requirement (μas) | Goal (μas) | Floor (μas) |
|---|---|---|---|---|
| Standard candles (residuals): | 5-9 | 50 | 25 | 200 |
| | 12 | 125 | 67 | 400 |
| | 15 | 500 | 250 | 1000 |
| Solar-Neighborhood Stars (residuals): | 5-9 | 50 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Brown Dwarfs (residuals): | 9 | 50 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Star forming regions (residuals): | 5-9 | 50 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Reference Frame (positions): | 5-9 | 50 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Stellar Astrophysics (residuals): | | | | |
| White Dwarfs: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Planetary Nebulae: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Subdwarf O/B Stars: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| HB Stars: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Galactic Structure (residuals): | 5-9 | 50 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 2000 |
| Relativity (positions): | 9 | 1000 | 500 | 2000 |
| Solar System (positions): | 9 | 2000 | 1000 | 10000 |

**Table 2-2. FAME Astrometric Proper Motions - Performance Requirements, Goals and Floor for the 2½-Year Mission**

| | *V* (mag) | Requirement µas/yr | Goal µas/yr | Floor µas/yr |
|---|---|---|---|---|
| Standard candles: | 5-9 | 70 | 25 | 200 |
| | 12 | 125 | 67 | 400 |
| | 15 | 500 | 250 | 1000 |
| Solar-Neighborhood Stars: | 9 | 70 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Brown Dwarfs: | 5-9 | 70 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Star forming regions: | 5-9 | 70 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Reference Frame: | 5-9 | 70 | 25 | 500 |
| | 15 | 500 | 250 | 1000 |
| Stellar Astrophysics: | | | | |
| White Dwarfs: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Planetary Nebulae: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Subdwarf O/B Stars: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| HB Stars: | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Galactic Structure: | 5-9 | 70 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 2000 |
| Relativity: | | | | |
| Solar System: | | | | |

**Table 2-3. FAME Astrometric Parallaxes - Performance Requirements, Goals and Floor for the 2½ Year Mission**

| | *V* (mag) | Requirement (μas) | Goal (μas) | Floor (μas) |
|---|---|---|---|---|
| Standard candles: | 5-9 | 50 | 25 | 200 |
| | 12 | 125 | 67 | 400 |
| | 15 | 500 | 250 | 1000 |
| Solar-Neighborhood Stars: | 5-9 | 50 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Brown Dwarfs: | 5-9 | 50 | 25 | 200 |
| | 15 | 500 | 250 | 2000 |
| Star forming regions: | 5-9 | 50 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 1000 |
| Reference Frame: | 5-9 | 50 | 25 | 500 |
| | 15 | 500 | 250 | 1000 |
| Stellar Astrophysics: | | | | |
| White Dwarfs: | 12 | 125 | 67 | 500 |
| | 15 | 400 | 250 | 2000 |
| Planetary Nebulae: | 12 | 125 | 65 | 500 |
| | 15 | 500 | 250 | 1000 |
| Subdwarf O/B Stars: | 12 | 125 | 65 | 200 |
| | 15 | 500 | 250 | 1000 |
| HB Stars: | 12 | 125 | 65 | 300 |
| | 15 | 500 | 250 | 1000 |
| Galactic Structure: | 5-9 | 50 | 25 | 500 |
| | 12 | 125 | 67 | 500 |
| | 15 | 500 | 250 | 2000 |
| Relativity: | | | | |
| Solar System: | | | | |

### 2.3.2 Photometry

#### 2.3.2.1 Passband Requirements – Astrometric and SDSS Filters

Accurate astrometry with FAME requires knowledge of the color of each star, so that the point spread function, which is color dependent, can be modeled properly. Because colors are not available for most of the faint stars in the FAME sample, the mission will incorporate filters that reproduce the SDSS g’, r’, i’, and z’ passbands to provide the needed color information. The photometric measurements provided by FAME will also enable additional science, such as studies of stellar variability and astrophysics, and the determination of interstellar extinction to individual stars.

The FAME photometric performance requirements, goals and floor in mmag for the 2½-yr mission are specified in Table 2-4 for the astrometric and SDSS passbands. In some cases the performance for individual measurements is specified. The astrometric filter is designated w.

**Table 2-4. FAME Passband Requirements - Photometric Performance Requirements, Goals and Floor for the 2½ Year Mission**

| | Filter | *V* (mag) | Requirement (mmag) | Goal (mmag) | Floor (mmag) |
|---|---|---|---|---|---|
| Standard candles (non-variable stars, mission): | w | 12 | 10 | | |
| | SDSS | 5-9 | 1 | 0.2 | 10 |
| | | 12 | 2 | 1 | 10 |
| | | 15 | 8 | 3 | 20 |
| Solar Neighborhood stars (per observation): | w | 10 | 3 | | 20 |
| | w | 5-9 | 2 | | |
| | | 15 | 10 | | |
| Brown Dwarfs (per observation): | w | 5-9 | 3 | 1 | 5 |
| | | 12 | 12 | 4 | 20 |
| Star forming region | | | | | |
| (per observation) | w | 5-9 | 2 | 1 | 5 |
| | | 12 | 8 | 4 | 20 |
| (mission) | SDSS | 5-9 | 1 | 0.2 | 10 |
| | | 12 | 2 | 1 | 10 |
| | | 15 | 10 | 3 | 20 |
| Reference Frame: | w | 5-9 | 10 | | |
| Photometry: | | | | | |
| (per observation) | w | 5-9 | 2 | 1 | 10 |
| (mission) | SDSS | 5-9 | 1 | 0.2 | 10 |
| | | 15 | 8 | 3 | 20 |
| Stellar Astrophysics: | | | | | |
| Solar-type stars (per observation): | w | 5-9 | 2 | 1 | 20 |
| | | 12 | 8 | 4 | 20 |
| Radial Pulsators (per observation): | w | 5-9 | 2 | 1 | 30 |
| | | 12 | 8 | 4 | 30 |
| Non-radial Pulsators (per observation): | w | 5-9 | 3 | 1 | 30 |
| | | 12 | 10 | 4 | 10 |
| Non-Radial Pulsators (mission): | w | 9 | 1 | 1 | 5 |
| | | 12 | 2 | 1 | 10 |
| | | 15 | 8 | 3 | 10 |
| Interstellar matter (mission): | | 12 | 2 | 1 | 20 |
| Galactic Structure (mission): | w | 5-9 | 1 | | |
| | | 12 | 2 | | |
| | | 15 | 8 | | |
| | SDSS | 5-9 | 1 | 0.2 | 5 |
| | | 12 | 2 | 1 | 10 |
| | | 15 | 8 | 3 | 10 |
| Relativity: | | | | | |
| Solar System: | | | | | |

#### 2.3.2.2 Passband Goals – Astrophysical Filters

If allowed by budget and schedule, the SDSS g’, r’, i’, and z’ filters and astrometric + ND combinations shall be replaced by the filter set specified in Table 2.5. In this scheme the narrow-band F745 TiO continuum filter would replace the astrometric + ND 2 mag combination, and the F745 + ND 2 mag combination would replace the astrometric + ND 4 mag combination.

**Table 2-5. FAME Passband Goals – Filter Characteristics**

| Filter | Center (nm) | FWHM (nm) | Comments |
|---|---|---|---|
| Astrometric Filters | | | |
| w | 700 | 300 | wide astrometric filter |
| F745 | 745 | 30 | TiO continuum; replaces w+ND2 |
| F745+ND2 | 745 | 30 | TiO continuum; replaces w+ND4 |
| Astrophysical Filters | | | |
| F422 | 422 | 75 | “Strömgren b” |
| F466 | 466 | 50 | “Strömgren v” |
| g’ | 480 | 141 | SDSS |
| r’ | 625 | 139 | SDSS |
| i’ | 769 | 154 | SDSS |
| F875 | 875 | 85 | CaII triplet; replaces SDSS z’ |

# 3. FAME SUPPORTING NOTES

## 3.1 Distance Scales

### 3.1.1 Cepheid Distances

The Galactic Population I Cepheid variables have been used for many years to calibrate the cosmological distance scale. However, due to limitations in establishing the absolute magnitudes of the Galactic Cepheids, it has not been possible to calibrate the cosmological distance scale to the desired accuracy. As a temporary device, investigators have adopted the Magellanic Clouds as the reference point for extragalactic distances. It has become apparent, however, that effects such as age and metallicity differences between the Magellanic Clouds, the Galaxy and distant galaxies introduce a source of systematic error into the distances. FAME can address this problem by deriving much better distances to the Galactic Cepheids. FAME will be able to measure accurate parallaxes to 70 Galactic Cepheids and determine the zero-point of the cosmological distance scale to an accuracy of 0.01 mag. A weakness of the FAME zero point will be that it will only include 16 Cepheids with periods greater than 10 days, which is the important region of overlap with the extragalactic Cepheids. If one ignores all external information on the slope of the period-luminosity relation, the zero-point error will be increased to 0.02 mag.

The dominant source of error in the FAME absolute-magnitude calibrations of Cepheids (and open-cluster stars) will be the uncertainty in the interstellar extinction, since these Population I objects lie in the Galactic plane and are often heavily obscured. We use two methods to estimate the uncertainty in the extinction estimates. First, we use the data of Feast & Catchpole (1997) and Feast & Whitelock (1997), who have obtained a calibration of the period-luminosity-color relation for 220 Galactic Cepheids based on ground-based photometry and Hipparcos parallaxes. Feast & Whitelock (1997) list the observed (*<B>*-*<V>*) and *E(B-V)* values for each star, from which we obtain the "intrinsic" $(<B>-<V>)_0$ values. Laney & Stobie (1994) provide a relation between the intrinsic color of a Cepheid and the logarithm of its period, and from the difference between the observed and predicted intrinsic color, we estimate the error of the observed value assuming initially that the predicted value is without error. The rms of the difference is 0.07 mag. However, since the width of the Cepheid instability strip is ~0.2 mag, most of this scatter is due to real deviations from the period-color relation and not errors in the reddening estimates. We estimate the reddening error to be the quadrature difference of these two effects, 0.04 mag. Second, we compare the independent reddening estimates done by Fernie (1990) and Dean, Warren, & Cousins (1978) and find an rms difference of 0.03 mag, in good agreement with the first estimate. We combine the two to obtain $\sigma_{E(B-V)}$=0.035 or $\sigma_{Av}$=0.1 mag.

Because Cepheids are confined to the Galactic plane, their number grows as distance squared. It is then straightforward to show that the error in the zero-point determination is approximately given by:

$$\sigma_{(\mathrm{zero-point})} = \frac{\sigma_{Av}}{\sqrt{N_{eq} * \ln\left(D_{cut} / D_{eq}\right)^2}}$$

where Deq=1 kpc is the Cepheid distance at which the fractional parallax errors are equal to $[\ln(10)/2.5] * \sigma_{Av}$, $N_{eq}$ is the number of Cepheids within this distance, and $D_{cut}$ ~ 2.5 kpc is the distance at which Cepheids reach V~9 (beyond which the fractional parallax errors increase as the square of the distance, rather than linearly). Cepheids beyond this distance do not contribute significantly to the zero-point determination. Considering all Cepheids, $N_{eq}$=70. Considering only those with periods greater than 10 days, $N_{eq}$=16.

From this formula, one can construct the following table:

| $\sigma_\pi$ (V=9) (µas) | $\sigma$ (zero-point) (all Cepheids) (mag) | $\sigma$ (zero-point) (*P* > 10 days) (mag) |
|---|---|---|
| 50 | 0.008 | 0.017 |
| 100 | 0.013 | 0.027 |
| 200 | 0.022 | 0.046 |

For Cepheids, the critical magnitude range is V<9. Descoping FAME by a factor of two would significantly reduce the precision of the zero-point determination, and by a factor of four would seriously reduce it. It would still be worth doing the problem at $\sigma_\pi$ (V=9) = 200 μas, but not much beyond that.

### 3.1.2 RR Lyrae Distances

#### 3.1.2.1 Parallaxes

We rely here mainly on parallaxes of relatively nearby RR Lyrae stars. Therefore, we are sensitive mainly to the mission precision at the bright end. Specifically, there are 73 RR Lyraes for which the nominal mission characteristics would yield parallax errors better than 10%. It does not do much good to get errors much better than 10% because of intrinsic scatter in the absolute magnitudes of RR Lyraes. Stars with parallax errors much worse than 10% are not useful because 1) they contribute very little statistically even if they did not suffer from systematics, and 2) one must worry about systematics at a low and undetectable level.

The mean RR Lyrae absolute magnitude can be measured to 0.022 mag from these 73 stars. If the mission were degraded by a factor of two, the same 73 stars would yield 0.031 mag. Another factor of two would degrade the result to 0.04 mag. If the errors increased beyond that, FAME would have little impact on the calibration of RR Lyrae absolute magnitudes. The 10% parallax measurement limit (i.e., the 73rd star) has $V$=12 mag, so it is at $V$=12 mag that the FAME precisions are important for RR Lyrae parallaxes.

#### 3.1.2.2 Statistical Parallax

What is required is only that FAME achieve proper motion precisions corresponding to about 20 km/s at 3 kpc, i.e., 1.4 mas/yr at $V$=13 mag. This is almost an order of magnitude worse than the nominal mission performance. FAME could fail for most other applications and still be a resounding success here.

### 3.1.3 Subdwarf Distances

As will be outlined below, parallax errors better than 10% are required for this application, but it is not necessary to drive the parallax errors much below 3%. With the nominal FAME performance, there are about 700 stars known with [Fe/H]<−1.5 for which FAME could get 10% parallaxes. The great majority of these are relatively blue (0.4<$B$-$V$<0.8 mag) and hence intrinsically bright (5<$M_V$<7 mag). The number of such stars falls approximately inversely as the precision cubed. This would be bad but tolerable for a factor of 2 degradation in the FAME performance, but would be terrible for a factor 4. One major problem as the number of stars falls is that the sampling of the two-dimensional space ($B$-$V$,[Fe/H]) of subdwarfs becomes worse. It would then be difficult to determine whether the theoretical tracks are correct, simply because they would be so poorly sampled. One happy note: faint subdwarfs (Mv>7 mag that are so rare in the known sample, are all quite nearby and thus will have acceptable parallax errors even if the mission performance is degraded. Thus, as the sample size falls from degradation, it will lose mainly from the well-sampled color range. To put it differently, FAME should lead to the identification of large numbers of relatively nearby, cool, intrinsically faint, low-mass, high-velocity metal-poor subdwarfs.

### 3.1.4 Open Clusters Distances

Open star clusters have historically played a major role in establishing distances in the Galaxy, using the main sequence fitting technique. A few of the open clusters are particularly important in setting the zero-point for the Cepheid period-color-luminosity relation because they contain Cepheid variables.

In the Hyades cluster, close enough to apply the moving cluster technique, the main sequence has historically been used to define a standard main sequence, whose locus served to determine the distance moduli of more distant clusters. Main sequence fitting, now understood to require corrections for differences in [Fe/H] among clusters, still plays an important role in establishing the Galactic and extragalactic distance scales. Thanks to Hipparcos, the once controversial distances to the Hyades and some other nearby clusters have been determined with improved accuracy.

However, a controversy has arisen regarding the distance to the Pleiades, Praesepe, and Coma clusters, whose main-sequence fitting distances disagree with their Hipparcos distances. Pinsonneault et al. (1998), using theoretical isochrones based on the best stellar models then available, and including corrections for differences in [Fe/H] between clusters, conclude the that agreement between their models and the Hipparcos data cannot be achieved without adopting an anomalously large helium abundance for the Pleiades. They reject this solution and raise the possibility of systematic errors in the Hipparcos data larger than the quoted errors (see also Narayanan & Gould 1999a and b). Otherwise, they argue that taken at face value, the Hipparcos result raises the possibility that something important is missing in the stellar models.

FAME observations provide a unique opportunity to resolve the issue of possible systematic errors in the Hipparcos data. The outcome will be either the confirmation of the Hipparcos open-cluster distances, or the determination of new, more reliable, distances free of the Hipparcos systematic errors.

#### 3.1.4.1 Open Cluster Memberships

We must ensure that the targets selected to determine the distances of open clusters are actually cluster members. The most effective way to do that is to use proper motions. At $V$=15 mag, the accuracy of the FAME proper motions is 0.5 mas/yr, which is much better than the 1.0 mas/yr that is normally required for reliable proper-motion membership determinations. We need to ensure that complete samples of stars in the vicinity of all the open clusters within about 1 kpc of the Sun are included in the FAME Input Catalog so that we will be able to derive memberships.

#### 3.1.4.2 Correlated Systematic Errors

We have assumed so far that there are no systematic errors that would dominate the quoted accidental errors. This issue is of considerable interest when we consider averaging the parallaxes of several stars that are members of a star cluster to obtain a more accurate mean parallax of the cluster, or for a member Cepheid. However, if the parallax errors are correlated on an angular length scale comparable to the cluster dimensions, then the mean parallax of several cluster members may not result in a more accurate cluster parallax. Such effects have been reported for the Hipparcos parallaxes in the region of the Pleiades and Hyades clusters by Narayanan and Gould (1999a, b) and Pinsonneault et al. (1998). The half-amplitude of the Hipparcos parallax zero-point errors is about 1-2 mas on an angular scale of 1-2 degrees. Since the average Hipparcos accidental parallax error is about 1.0 mas, little is gained by averaging more than two or three members to obtain a mean cluster parallax. Since FAME has a scanning law similar to that of Hipparcos, and a reduction scheme necessarily similar to that of Hipparcos, it is probable that it will also have zonal errors similar in size to the individual errors at the bright end. On the other hand, the ratio of FAME systematic to accidental errors should be somewhat smaller than those of Hipparcos due to the much higher density of stars observed by FAME, 1000 versus 2.5 stars per square degree. We must be very careful about assuming that any number of stars on a small angular scale can be averaged to derive a mean distance with greater accuracy than the individual accuracies. This effect will be important for the parallaxes, but less important for the determination of memberships based on proper motions.

Descoping the astrometric accuracy by a factor of two will have a small effect on the determination of memberships, but a major effect on the distance determinations for the clusters. On the other hand, if the correlated systematic errors can be controlled, then averaging four times more stars in a cluster will compensate for the reduced parallax accuracy. A reduction in the magnitude limit of FAME would have a major impact, as that would considerably reduce the number of star clusters within the reach of FAME.

### 3.2 Mass and Luminosity Calibration of Solar-Neighborhood Stars

The calibration of stellar luminosities in the solar neighborhood, including both Population I and II stars, will be improved by FAME. With an accuracy some 20 times better than Hipparcos, it will be possible to calibrate the luminosity axis of the HR diagram for nearly all types of stars and to enable diverse studies of stellar evolution and other interesting science. In the case of the Population II subdwarfs, it will enable the determination of the distances and ages of Galactic and extragalactic globular clusters with unprecedented accuracy.

FAME will determine the mean absolute magnitude of the bright massive supergiants of Mv = –5 mag to an accuracy of 0.02 mag. The FAME parallax error budget of 50 µas for stars brighter than $V$=9 mag yields a fractional parallax accuracy ($\delta\pi/\pi$) = 0.05, or a distance modulus accuracy of 0.11 mag. at a distance of 1000 pc. For these bright stars, the standard luminosity function predicts between 30 (assuming they are concentrated towards the disk) and 230 (spherical volume) within a volume of radius of 1000 pc, and height ±100 pc for the cylindrical case. Even in the restricted cylindrical case, the accuracy of the mean absolute magnitude is an unprecedented 0.02 mag. This discussion assumes that the interstellar extinction can be determined with sufficient accuracy.

For the fainter stars in the HR Diagram the luminosity function increases rapidly, and there will be 300,000 stars brighter than $V$=10 mag with Mv < 0 mag. These stars will have individual absolute magnitudes determined to better than 0.11 mag. With this level of accuracy for large numbers of stars, it will be possible to calibrate the mean absolute magnitudes of small groupings of stars throughout the upper part of the HR diagram. Beyond $V$=10 mag, the accuracy of the FAME parallaxes decreases to about 500 μas at $V$=15 mag. The standard luminosity function predicts that there will 40 stars of Mv = 15 mag within a volume of radius 10 pc. Nearly all of these faint stars have had their luminosities adequately calibrated from modern ground-based parallaxes, so FAME will have its greatest impact on the calibration of stars with Mv brighter than 5 mag.

Methods have been developed to correct for systematic errors in luminosity calibrations due to the bias introduced when selecting stars with parallaxes larger than some given value (e.g. Lutz & Kelker 1973). However, an accurate knowledge of the true, and unknown, spatial distribution of the sample is necessary for the implementation of these methods. Indirect methods relying on the distribution of proper motions of the sample stars can be used to infer the true parallax distribution. FAME's large sample of accurate parallaxes will put us in the unique position of being able to determine the required corrections independently by breaking the sample into discrete parallax groupings.

The number of subdwarfs will be increased by at least a factor of 20 over those used with the Hipparcos data; hence again the accuracies are extremely favorable.

Descoping by a factor of two will still allow the calibration of the HR Diagram 10 times better than Hipparcos at all magnitudes.

FAME will make significant contributions to our knowledge of the mass-luminosity relation by enabling determinations of the individual masses of the components in many binary stars. In some cases it will be possible to use the positions provided by FAME to solve directly for all the parameters of an astrometric orbit, including the mass ratio and therefore the individual masses. More commonly the FAME astrometry will be combined with spectroscopic observations of radial velocities to derive the orbital parameters and individual masses. Spectroscopic binaries with double-lined orbital solutions are an important case, because a solution for the orbital inclination using the FAME astrometry then allows the individual masses to be derived. Another important opportunity for deriving accurate masses will be the eclipsing binaries identified by FAME, which can then be followed up with ground-based spectroscopy and photometry.

The masses and radii of more than 150 stars in eclipsing binaries have already been derived with accuracies better than 2%, but the vast majority of these stars are more massive than the Sun, very few are M dwarfs, and almost none are young pre-main-sequence stars on the one hand, or old metal-poor high-velocity halo stars on the other hand. Other areas of the HR diagram that are poorly represented by accurate mass determinations are evolved stars such as subgiants and giants, and very massive stars. FAME astrometry will contribute to improving our knowledge of stellar masses in all these populations.

### 3.3 Brown Dwarfs and Planets

Radial-velocity surveys of a few thousand nearby solar-type stars have led to the discovery more than five dozen unseen companions with minimum masses below the substellar limit, in the mass range from 0.15 to 80 $M_J$. Essentially all have orbital periods shorter than 5 years. An analysis of the secondary mass distribution for low-mass companions suggests that the frequency of companions drops off rapidly near the substellar limit of 80 $M_J$ as the mass crosses from the stellar to brown-dwarf regime, while the frequency of gas giant planets rises toward lower masses (e.g. Mazeh et al. 1998). The transition region between gas giant planets and brown dwarfs appears to lie in the range of 10 to 30 $M_J$, although this result is still very preliminary and uncertain because of the small number of systems available for analysis and because of the sin($i$) ambiguity inherent in radial-velocity detections. Wide binary stars appear to be equally hospitable to the formation of gas giant planets as are single stars.

FAME will provide a definitive determination of the frequency of solar-type stars orbited by brown dwarf companions in the mass range 10 $M_J$ to 80 $M_J$ and with orbital periods up to about twice the duration of the mission (i.e., ten years, with the extended mission). This will include an exploration of the transition region between gas giant planets and brown dwarfs. To be specific, FAME has the sensitivity to derive orbits for companions with masses down to 8 $M_J$ around 24,000 solar-type stars within 100 pc, 4 $M_J$ around 3,000 solar-type stars within 50 pc, and 2 $M_J$ for 375 of the nearest solar-type stars within 25 pc. These numbers are based on the results from simulations carried out for the GAIA mission (Lattanzi et al. 2000), adapted to the FAME mission requirement of 50 μas astrometric accuracy. The goal for FAME would be to lower these detection limits by a factor of two, allowing 1 $M_J$ planets to be detected around solar-type stars within 25 pc. The floor for FAME would allow the nominal detection limits to rise by a factor of four.

In addition, FAME will be able to derive orbital inclinations for many of the stellar and substellar companions with spectroscopic orbits, thus eliminating the sin(*i*) ambiguity in the masses. For the 51 Peg-type systems with hot Jupiters in short-period orbits, FAME will be able to search for additional companions in much wider orbits. The discovery of additional planetary-mass companions would be especially significant, because it would provide evidence for planetary systems (as opposed to just the largest planet) orbiting solar-type stars, as in the case of the Upsilon Andromedae system of three planets (Butler et al. 1999).

The first confirmation of an extrasolar planet, by transit photometry of the star HD 209458 (Charbonneau et al. 2000; Henry et al. 2000), emphasizes the possibility that FAME can detect planets photometrically as well as astrometrically. A transit by a Jupiter-sized planet (or a brown dwarf star) results in a dimming of the primary star by about 10 mmag. FAME's required photometric accuracy for individual measurements at the 3 mmag level for *V*=9 mag stars is sufficient to allow FAME to search for transits by substellar companions. [We exclude 15th magnitude stars, because their expected photometric accuracy of 40 mmag is insufficient for this purpose.] Typical planetary transits last on the order of a few hours. FAME will observe each star roughly 1000 times, or only about once a day on average. However, because each star will be observed twice during a 40-minute scan, for three successive scans, each star will have 6 photometric observations over a two-hour time period, sufficient to identify at least a portion of a planetary transit. In most cases FAME will not have sufficient temporal coverage to determine an orbital period, but FAME's photometry should provide a powerful survey tool for the identification of transit candidates for subsequent follow-up using ground-based photometry.

FAME will also make an important contribution to subsequent space missions designed to search for planetary transits by terrestrial-sized planets, such as Kepler. Giant stars are so large that Kepler does not have sufficient photometric precision to detect transits by earth-sized planets orbiting giants. The effectiveness of the Kepler mission for detecting terrestrial-sized transiting planets can be improved by at least a factor of two by pre-selecting targets that are solar-type stars using the distances and the photometry in the SDSS and astrophysical filters provided by FAME.

## 3.4 Star-Forming Regions

### 3.4.1 Present Status

The nearest low-mass star-forming regions (SFRs) in our Galaxy lie at a distance of about 150 pc (e.g., Taurus-Auriga), and the nearest rich SFRs lie at about 450 pc (e.g. Orion). Regions forming truly massive stars are located at about 1 kpc or further (e.g., S106, NGC7538, W3). The stars in all these SFRs were mostly too faint to be observed by Hipparcos, and even for the brightest members of the nearest SFRs the Hipparcos distance errors amounted to 20% or worse. The improved photometric sensitivity and astrometric accuracy of FAME will allow large numbers of pre-main-sequence (PMS) stars in these SFRs to be surveyed efficiently.

Because accurate distances have been determined directly for only a handful of PMS stars, the distances to SFRs and giant molecular clouds (GMCs) are not well determined. As a result we have only a rough idea of how the SFRs regions are laid out in space, and our picture of the three-dimensional structure in SFRs is rather fuzzy.

Because direct distances are not yet available for most PMS stars, the usual procedure for identifying members of a SFR relies on circumstantial evidence of extreme youth, such as association with molecular material, excess infrared emission from circumstellar disks, strong lithium absorption, indicators of surface activity (X-ray or radio emission or optical/IR variability), and/or space motions similar to other nearby young stars. If this evidence supports membership, then a PMS candidate is assigned the distance adopted for the SFR.

The lack of direct distance determinations means that the luminosities and therefore the ages of individual PMS stars are also poorly determined. Moreover, the evolutionary tracks calculated for PMS stars are not yet well-established, despite a lot of recent work. The net result is that the ages for PMS stars are uncertain by factors of two and more.

Although radial velocities accurate to 1 or a few km/s have been determined for a few hundred PMS stars, in general the space motions of individual PMS stars have not been determined, and very little is known about the kinematics of SFRs.

### 3.4.2 The Promise of FAME

Many important aspects of star formation are largely unknown due to the many uncertainties in the distances, memberships, spatial distributions, motions, luminosities, and ages of young stars in SFRs and clusters. FAME will reduce many of these uncertainties, thereby allowing significant advances in several important areas of star-formation science.

#### 3.4.2.1 Distances, Memberships, and Kinematics of Star-Forming Regions

FAME will determine distances to individual bright stars in the nearest SFRs to an accuracy of about 1 percent. Thus, we can use the bright stars to get very accurate distances to the interesting SFRs, their substructures, and young clusters within a few hundred parsecs.

At the nominal limit of $V$=15 mag the distances to individual PMS stars in the nearest SFRs will be better than 10%. For the many members brighter than this limit, say in the magnitude range 12 to 14, the parallax accuracy will be good enough to allow a lot of progress in determining whether stars that are grouped together on the sky are physically associated.

Another powerful tool for identifying members of SFRs and young clusters is the space motion of individual stars. The proper motions from FAME will be especially useful, because the velocity dispersion in SFRs and young clusters is on the order of 1 km/s, which corresponds to 200 µas/yr at a distance of 1 kpc. Even with an astrometric performance degraded to 500 µas/yr, the level expected at $V$=15 mag, the FAME proper motions will still provide useful information on memberships. If radial velocities can also be measured, e.g., to about 1 km/s using complementary ground-based observations, this will strengthen the membership assignments.

If space motions accurate to 1 km/s can be determined in large numbers, then we can start to study the kinematics of SFRs and their substructures. If the age estimates are good enough, we can trace the motions of individual stars back to the clusters and associations where they formed. The goal here is to understand in detail how PMS stars dissolve into the general field and interstellar medium from the sites of formation.

The velocity dispersion of the gas in GMCs has been determined from observations of the line widths, and ranges from 0.5 to 1.5 km/s, but we don't know whether the recently-formed stars in GMCs share this dispersion. Proper motions from FAME could address this issue, especially if supplemented with radial velocities.

#### 3.4.2.2 Establishing the Zero-Point of Stellar Evolution

The earliest phases of PMS stellar evolution (ages less than 3 Myr) are not well understood. However, FAME will determine the distances and hence the luminosities of many very young stars in nearby SFRs, spanning a wide range of masses (B stars in Orion to M stars in Taurus-Auriga and Chamaeleon). When combined with existing optical / IR spectra, these data will define the locus of the stellar birthline in the HR diagram. Establishing this birthline is essential for anchoring and advancing both protostellar formation and early stellar evolution. Determining the ages and masses of young stars are key to making these advances.

##### 3.4.2.2.1 Ages

Once memberships have been established, the accurate distances derived from the brighter members can be used to place all the stars down to $V$=15 mag accurately on an HR diagram for its SFR or cluster. Then evolutionary models can be used to derive individual age estimates. Of course, this step requires additional photometric and/or spectroscopic information, such as extinction, reddening, and/or effective temperature.

Young PMS clusters are targets of special interest, because they represent groups of stars that formed together out of the same material, and thus are especially useful for testing the theoretical models of stellar evolution. In young clusters FAME can study the formation and early evolution of massive stars, even out to distances as large as 1 kpc. Such studies of very luminous young stars in our own Galaxy would help us understand the star-formation that we observe in other galaxies, where it is much harder to study low-luminosity stars.

##### 3.4.2.2.2 Masses

FAME will also be able to determine the orbital inclination for selected PMS binaries with spectroscopic orbits, thus contributing to our knowledge of the masses for PMS stars (there are at present only a handful of direct mass determinations for PMS stars less massive than the Sun, none of them accurate enough to allow definitive tests of stellar models for PMS stars). FAME should also detect many eclipsing PMS stars, which can then be followed up spectroscopically to provide mass determinations for the double-lined systems. Accurate masses for PMS stars will allow us to carry out fundamental tests of the evolutionary tracks predicted by the theoretical models, assuming that metallicities are available from complementary ground-based observations.

#### 3.4.2.3 Evolution Towards the Main Sequence

FAME will allow significant progress in understanding the evolution of stars and their planetary systems from early PMS phases towards the main sequence. We now explain how FAME distances, proper motions, and photometry will advance our understanding in these areas.

##### 3.4.2.3.1 Nearby Loose Associations

A recent development that has attracted a lot of interest in the star-formation community is the discovery of a few nearby loose associations of young stars, e.g., the TW Hydrae association at a distance of about 50 pc. These poor groups were not previously recognized because they were lost in the maze of field stars. Hipparcos played an essential role in identifying the half-dozen such associations recently discovered, all within about 100 pc. When combined with indicators of stellar youth (e.g. from 2MASS, Sloan, and X-ray surveys), the distances and proper motions provided by FAME will allow the identification of additional members for the associations already recognized, and the identification of additional such associations. Even an astrometric performance as poor as 1 mas at $V$=15 mag could still make an important contribution to the identification of new associations and additional members.

Although these associations tend to be older (3 - 30 Myr) than the traditional SFRs, they have the major appeal that they are nearby and can therefore be studied in more detail, e.g. for the astrometric signature of planetary companions. Identifying these associations is also important for follow-up studies of stellar and planetary-system evolution. Very little is known about the stars and planetary systems in this age range. This is an important stage in the evolution of young stars, because it is the period when stars dissipate their circumstellar disks (perhaps forming planets), decrease their radius (and spin up), and become less active.

##### 3.4.2.3.2 When Do Planets Form?

One of the hottest fields in astronomy is the study of extrasolar planets, and one of the most interesting questions in this field is when do planets form? Although FAME will not have sufficient astrometric accuracy to detect giant planets around PMS stars in the traditional star-formation regions, it can make an important contribution by identifying the optimum young targets for a pointed mission with much higher astrometric accuracy, such as the Space Interferometry Mission (SIM). This is just one of many examples where FAME will be an important precursor mission for SIM and subsequent space missions such as the Terrestrial Planet Finder (TPF).

### 3.4.3 Surface Activity and Rotation

FAME will supply photometric measurements good to better than 1% from hundreds of visits to each star. This will allow an assessment of the photometric variability of PMS stars in general, and the determination of photometric rotation periods in particular. As stars evolve towards the main sequence, and even after they have settled onto the main sequence (e.g. in young clusters), their rotation eventually slows down and their chromospheres become less active. However, their rotational velocities and activity levels are expected to increase when they initially evolve from the youngest T Tauri phases. This is because their radii decrease more quickly than the onset of rotational braking (presumably by magnetic coupling). The photometric periods and activity levels provided by FAME should make a major contribution to our understanding of how the rotation and activity of young stars evolve. The members of loose associations, which are midway in age between the SFRs and young open clusters, are likely to play a crucial role in this kind of study.

### 3.4.4 Photometric Binaries

The accurate photometry and distances provided by the FAME mission will allow the identification of photometric binaries in clusters. The classic definition of a photometric binary is a star that lies above the single-star main sequence on the cluster color-magnitude diagram. Because FAME provides so many visits to each star, a new definition of a photometric binary should be possible, namely targets that show two photometric periods due to rotation and spots on the two stars in a binary. Studies of photometric binaries will contribute to our understanding of the frequency of binaries. Do young clusters show the same result as has been reported for field stars in SFRs, that the frequency of binaries is higher in the youngest populations than for older populations such as the solar neighborhood?

## 3.5 Reference Frames

The International Celestial Reference System (ICRS) recently adopted by the International Astronomical Union (IAU) employs an International Celestial Reference Frame (ICRF) that is based on the radio positions of extragalactic sources. The extragalactic sources should display no appreciable proper motion at the µas level because of their vast distances from the solar system barycenter. Thus, the frame should not display degradation when transformed from epoch to epoch.

The ICRF source positions are obtained by measurements made with very long baseline interferometry (VLBI) at a wavelength of 3.7 cm. The accuracy of the individual positions of the 212 primary sources making up this frame is of order 300 µas. The accuracy of the positions is limited by the Earth's atmosphere. There are approximately 400 additional sources, which are candidates for inclusion in the frame. The precision of the frame is of order 20 µas.

The optical frame now in use is based on the Hipparcos mission. The individual star positions are accurate to of order 1 mas at epoch 1991.25. The accuracy of these positions is deteriorating at the rate of about 1 mas/yr due to the uncertainties in the proper motions. The Hipparcos and Tycho catalogs do not contain any compact extragalactic sources, because they are limited to objects brighter than $V$=12 mag.

FAME will result in a catalog of positions for more than a million stars with accuracies in position, parallax, and proper motion of better than 50 µas, 50 µas, and 70 µas/yr respectively. A FAME reference frame will be established whose precision will be of order 1 µas. In addition FAME will observe over 100 extragalactic sources and stars that display compact radio emission. These measurements will be used to transform the FAME frame onto the ICRF. In addition, the observations of the extragalactic sources will be used to minimize temporal rotations of the FAME frame due to the proper motions of the stars making up the FAME frame. The rotation of the FAME frame should be less than 60 µas/yr. The precision of the FAME frame will lead to it replacing the present ICRF as the international standard. The FAME reference frame will include most of the grid stars for the SIM, as it will contain stars down to $V$=12 mag. The FAME frame will also enable detailed comparisons of radio/optical emission mechanisms associated with late-type stars, stars with associated maser emission, and compact extragalactic sources.

## 3.6 Stellar Astrophysics

We now consider how FAME will contribute to improving our understanding of stars that have left the main sequence, particularly white dwarfs, planetary nebulae central stars, subdwarf O/B stars, and horizontal-branch stars. Most of these old stars are distant, so they drive the FAME astrometric requirements in the range $V$=12-15 mag.

### 3.6.1 White Dwarfs

There are now approximately 100 white dwarfs (WDs) with parallax errors better than 10%. Many more must be observed with this accuracy to determine the space density, luminosity function, mass spectrum, and production rate of these stars. Determining these values will also illuminate how these objects evolve from hydrogen to helium-dominated atmospheres and will help identify particularly unusual objects.

There are approximately 400 WDs estimated to be brighter than $V$=15 mag, and most will have distances <250 pc. We require that FAME determine their parallaxes with less than 10% uncertainty, leading to a parallax uncertainty requirement of 400 µas at $V$=15 mag. FAME observations of a magnitude-limited sample of WDs will have far greater scientific value than present WD catalogs that, for cool WDs, are based on selection by proper motion and therefore have a kinematical bias. If the parallax accuracy at $V$=15 mag is degraded by a factor of 5 (to 2 mas), the hot WDs will no longer be identifiable from their parallaxes, but the ~150 cool WDs with D<50 pc will be, still a useful result. Larger errors will prevent the data from being useful. This sets the parallax uncertainty floor. In Tables 2-1 through 2-3 we also specify the astrometric performance for $V$=12 mag, the apparent magnitude appropriate for relatively close and young WDs.

Combined with photometric and spectroscopic data (easily acquired at ground-based observatories), FAME parallax measurements will allow determinations of the distances, luminosities, radii, and masses (from their mass-radius relation) of these 400 WDs, thus enabling the research discussed above.

### 3.6.2 Planetary Nebulae

Only 11 planetary nebulae (PNe) have had the parallaxes to their central stars determined to 3-$\sigma$ accuracy. This is inadequate for understanding the nebular physics, space density, and production rate of these objects. The parallaxes of at least as many new PNe must be determined in order to understand these objects better and how they relate to WDs.

There are about 200 central stars of PNe known with $V$<15 mag. Most are too distant to allow a significant parallax measurement with FAME, but distances to PNe are so uncertain that we cannot reliably predict which ones will have a detectable parallax and which will not. We expect that about 20 will have significant (3-$\sigma$) detections with the required FAME accuracy of 500 µas at V=15 mag, 10 detections if the accuracy is reduced to 1 mas (floor), and 50 if it is improved to 250 µas (goal). Therefore, we will get useful measurements for any FAME accuracy better than 0.5 mas at $V$=14 mag and 1.0 mas at $V$=15 mag. Some PNe central stars will be as bright as $V$=12 mag, and we specify their accuracy requirements in Tables 2-1 through 2-3.

### 3.6.3 Subdwarf O and B Stars

Many subdwarf O and B (sdO/B) stars are on the extended horizontal branch at temperatures of 20,000-30,000 K. However, their origin and evolution are not well understood. Fewer than about 10 of these stars have significant (3-$\sigma$) parallax measurements, so observing 100 more would provide a much greater sample so that their space density, luminosity function, and production rate can be established. These determinations will provide major clues to how these objects evolve from the extended horizontal branch and how they lose their hydrogen envelopes.

We estimate that the absolute magnitudes of sdO/B stars are Mv ~ 2 mag, and approximately 100 objects will have significant parallax measurements (better than 3-$\sigma$) at the required performance of 125 µas at $V$=12 mag. Dropping the astrometric accuracy below 300 µas at $V$=13 mag (floor) will result in observing too few objects, while improving it to 67 µas at $V$=12 mag (goal) will allow significantly more objects to be observed with better distance determinations.

### 3.6.4 Horizontal-Branch Stars

Significant (3-$\sigma$) distances have been determined for fewer than 10 horizontal branch stars, so very little is known about how these stars are distributed in this part of the HR diagram or how they are distributed in the local halo of the Galaxy.

However, there are more than 1000 horizontal branch stars brighter than $V$=12 mag and with distances of 2 kpc or less. FAME will determine the distances to these objects with 4-$\sigma$ accuracies or better if it meets a parallax accuracy requirement of 125 µas at $V$=12 mag. Dropping this accuracy below 300 µas (floor) will result in accurate distance determinations for too few stars to be worthwhile. Tightening this to 67 µas (goal) will allow better determinations of the luminosities and distances for more objects, significantly improving the science yield.

## 3.7 Galactic Structure and Evolution

### 3.7.1 Dark Matter

#### 3.7.1.1 Dwarf Stars

The measurement of the local density of dark matter is sensitive to the total number of G-K stars (4<Mv<8 mag) that meet two criteria. First, proper-motion errors must be substantially smaller than their vertical velocity dispersion, e.g. smaller than 5 km/s, i.e., $\sigma_\mu$<(1 mas/yr)/$D$, where $D$ is the distance in kpc. Second, the fractional parallax errors must be smaller than 25%, i.e., $\sigma_\pi$<(250 µas)/$D$. Clearly, the second requirement places the more stringent requirement on FAME. If FAME accuracies at the bright end are degraded, it will not affect this project. If the precisions are degraded at the faint end, we will lose statistics roughly as the cube of the parallax error at $V$=15 mag. Since the relation is a power law, it is difficult to say exactly where the breakpoint is, but if FAME errors grow from 500 µas, to 1 mas, it would still allow very exciting science, while at a few mas, the improvement over present measurements would not be very dramatic. Also, if the FAME magnitude limit near the Galactic plane degrades from $V$=15 to $V$=14, the results would be adversely impacted.

#### 3.7.1.2 K Giants

Another approach to the dark matter problem is to use a large homogeneous sample of K giants, such as the one being acquired by Majewski, for which good classification spectra and relatively accurate radial velocities (< 5 km/s) will be available. This sample is a natural extension of the work being done for the SIM grid by Majewski and his colleagues. The K-giants have a relatively narrow luminosity function peaking near Mv = 0.8 mag.

This project requires determining the number versus height above the plane for this sample within a cone of 20 degrees around the two Galactic poles. In order to reach a kpc, and to obtain an accurate estimate for the mass volume density near the plane and for the total column density up to 1 kpc above the plane, we need parallaxes accurate to 125 µas at $V$=12 mag. If the performance is degraded so that the parallax accuracy is 200 µas at $V$=12 mag, the project can still be done well. But, a degradation to 500 µas at $V$=12 mag would render the results of questionable value.

### 3.7.2 Age of the Disk and Halo

#### 3.7.2.1 Age of the Disk

The problem is to determine the time of earliest formation of Population I disk stars, in order to age-date the early phases of the formation of the Galaxy. The method is to determine the locus of the faintest G and K subgiant stars in the HR diagram. These are stars that have passed through the main sequence termination point and are on their way to the base of the giant branch.

The two famous local stars of this type that are within 15 pc are δ Eri and μ Her A near $M_V$=3.7 mag, approximately the same as the subgiant branch of the old open cluster NGC 188. The metallicities of δ Eri and μ Her are normal for Population I. Their space motions are clearly old disk.

The HR diagram from Hipparcos for stars with $\delta\pi/\pi<0.1$ shows a ragged lower boundary near $M_V$=4.0, which corresponds to the subgiant locus expected for the oldest stars. However, the number of stars defining this locus is less than 20, and the parallax errors are too large. An error in absolute magnitude of 0.2 mag corresponds to an error of 20% in the age.

If we wish the ages to be determined to within 2%, the parallax errors must be kept to $\delta\pi/\pi$ = 0.01 (or 0.02 mag in absolute magnitude). For a parallax error of 50 µas, the distances of the subgiant stars that define the lower envelope must be 200 pc or less. The number of subgiants near $M_V$=4.0 within this distance is estimated to be at least 1000 (perhaps as large as 5000), which is excellent for this problem.

If the parallax error increases to 100 µas, we reduce the distance to 100 pc and the volume by a factor of 8 to keep $\delta\pi/\pi$ the same at 0.01. The number of subgiants decreases to 120 (or perhaps as large as 600), which is still quite adequate. We can relax $\delta\pi/\pi$ to 0.02 to recover a sample of 1000, and even with a 4% error in the age, that would still be remarkable. Hence, FAME is well suited for the problem even with 100 µas errors. The apparent magnitudes of the subgiants at 100 pc will be $V$=9 mag and $V$=10.5 mag at 200 pc. Descoping to 200 µas will still give an experiment that is 5 times more accurate than Hipparcos, and the project will still be feasible.

#### 3.7.2.2 Age of the Halo

The best way to determine the age of the Galaxy is to age-date the oldest globular clusters, for example by determining the absolute magnitude of the main-sequence turn-off in these clusters. The calibration of the absolute magnitudes of RR Lyrae stars and Population II subdwarfs in the field, discussed in section 3.1, will contribute significantly to this problem. Ground-based color-magnitude diagrams of high precision are available that tie the horizontal branch (residence of the RR Lyrae stars) with the main sequence.

### 3.7.3 Distances to Interstellar Clouds

#### 3.7.3.1 Technique

An understanding of the physics of interstellar clouds requires, among other things, a knowledge of the radiation field in which a cloud is immersed and a knowledge of the cloud mass. The former depends on the cloud location with respect to the nearby O and B stars. The latter depends on the distance from Earth, assuming the angular extent is known (by, for instance, an emission map in H I, CO, or some other feature, or an extinction map) and that column densities are known. Then, the mass depends on the square of the distance, for our purposes. The clouds in question may be 1-10 pc in size, but because the distances are not known, the physical dimensions are also unknown.

The distance to an interstellar cloud can be determined by picking some absorption signature that indicates a star lies beyond the cloud (e.g., Na I absorption or $E(B-V)$) and searching for the same feature in ever more distant stars, starting near the Sun, until the cloud signature is detected. The distance to the test stars must, of course, be very well known. In the case of the radiation-field determination, the distance of nearby O and B stars must be known as well. For a number of problems of interest, FAME can be used to determine all of the needed distances. For the problems discussed here, all the stars of interest are brighter than $V$=11 mag. In order to have an adequate density of field stars to locate a cloud to sufficient accuracy, it may be necessary to go to $V$=12 mag in some cases.

The technique has been applied numerous times, but never to the precision needed for the radiation field determination. Frisch and York (1983) mapped the local interstellar bubble around the Sun in H I absorption, showing that the elongated feature extends to 400 pc in the third quadrant of Galactic longitude, but lies within 50 pc in the direction toward the Galactic center. Frisch, Sembach and York (1990) used the growth of Na I absorption with distance toward Orion stars to locate the front side of Orion's Cloak (Cowie, Songaila and York, 1979) at 200 pc from the Sun. (Orion's Cloak is another large bubble of gas, centered, in this case, on the Trapezium and contained within Barnard's Loop.) Welty et al. (1989) showed that the isolated clouds of CO emission at high latitude (MBM clouds, Magnani, Blitz and Mundy 1985) are in some cases within 100 pc of the Sun, and therefore are not, as had been supposed, of extremely high mass. A number of extinction studies have been used to pin down cloud distances. Of particular interest here is the result by Seidensticker and Schmidt-Kaler (1989) that the Coal Sack nebula is between 180 and 240 pc (see below). More recently, Knude and Høg (1998) used Hipparcos and Tycho stars to map out the distances to several molecular clouds, including the Coal Sack nebula.

#### 3.7.3.2 Radiation Field of Particular Interstellar Clouds

The distance of a cloud from nearby O and B stars must be determined to an accuracy of 10 pc to make any headway in determining the effect of the interstellar radiation field on numerous interstellar parameters. At 500 pc, we need 40 μas parallax errors to determine that a star is within 10 pc of a cloud. Otherwise, one cannot tell if the cloud is immersed in the mean radiation field or in the local field near a star. For 100 μas parallax errors, useful work could still be done. Further degradation would render the program less compelling.

#### 3.7.3.3 Molecular Hydrogen

Molecular hydrogen absorption lines have been detected and analyzed in about 100 O and B stars within 500 pc of the Sun. These stars, observed by Copernicus and by FUSE, have $0.03<A_V<4.0$ mag. We know much about these particular clouds empirically, but detailed analysis of the cloud physics and chemistry depends on knowing the radiation field in more detail. One of the clouds for which $H_2$ is now observed is, in fact, the Coal Sack (Rachford et al. 2001), where more detailed analysis awaits the outcome of the proposed experiment with FAME.

The excitation of the upper rotational J levels (J>2) varies from 60 K (Snow et al. 2000) to 1000 K (ζ Pup, Morton 1978). It is presumed that this range reflects the distances of the clouds from nearby hot stars, because pumping of the high J levels of $H_2$ occurs when the UV photon density is high (Spitzer and Cochran 1973). Proving this simple presumption would be a major step forward and would allow further progress in understanding the creation and destruction of $H_2$. Some formation mechanisms should leave $H_2$ in excited rotation states, for instance. With exact knowledge of the radiation field and simple modeling, these effects could be looked for. A direct proof that $H_2$ is formed on grains may result from this research.

### 3.7.3.4 Constituents of Interstellar Clouds

The radiation field, along with cloud density, determines the equilibrium ratios of neutral and once-ionized species (e.g., $Na^o/Na^+$, $C^o/C^+$, $Mg^o/Mg^+$). Recent studies have shown that the observed ratios are inconsistent with pure radiative recombination. For an assumed radiation field, the ratios for different species give different densities, by as much as a factor of 10 (Welty et al 1999 a,b). The implication is that the other reactions are dominating the production of the neutrals; one suspected agent is a group of very large molecules (Lepp et al. 1988, Welty and Hobbs 2001). Note that we are talking about molecules with 20-40 atomic nuclei per molecule. Fixing the absolute radiation field and the geometric mean density, given the cloud distances, allows one to decide which species are being under produced and which are being over produced. That decision is a crucial one in the analysis of which large molecules may be present in the diffuse interstellar clouds. It should be pointed out that the other, very circumstantial, evidence for large molecules (>3 atomic nuclei) in diffuse clouds is the presence of hundreds of unidentified absorption lines in absorption spectra of diffuse clouds, referred to as the diffuse interstellar bands. Having ruled out other recognized options, researchers suspect that large molecules may be involved (Douglas 1977, Smith, Snow and York 1977, Herbig 1995). Thus, the solution of the electron density mystery noted above may lead directly to solving an 80-year-old spectroscopic problem in astronomy, namely, the origin of the diffuse interstellar bands.

### 3.7.3.5 Stars Inside Interstellar Clouds

It is uncertain how much interstellar material is accreted onto stars. By locating distances of interstellar clouds so precisely that a given star could be known to be inside or outside a cloud, one could make progress on this problem. In fact, an entirely new area of research could be created. Obvious candidates for this type of study are white dwarfs, where the accretion may affect surface abundances; field G stars, where the analogs of the heliosphere of the Sun may be suppressed by interaction with a cloud; and stars with detected planetary systems (Talbot and Newman 1977). In the last case, immersion in an interstellar cloud would have dramatic effects on the planetary atmospheres, largely because of the effect of interaction of $H_2$ in interstellar clouds with ions in the upper atmospheres of the planets.

### 3.7.3.6 Masses and Densities

The molecule $H_3^+$ has recently been detected in diffuse interstellar clouds (Geballe et al 1999). The column densities are much larger than expected based on current models of diffuse clouds. The very detection of the molecule outside of the darkest molecular clouds was a surprise. Knowledge of whether all the interstellar gas is concentrated at one location or, alternatively, spread over many, widely separated, clouds, is important in deciding how far one has to go in modifying existing models of cloud chemistry to explain the observations. For now, the indications are that in at least one striking case, the line of sight to VI Cyg OB2 No. 12, the gas is widely distributed (McCall et al 1998), deepening the mystery of how $H_3^+$ can be present at all. The delineation of the material into specific locales on the sightlines in question can be done using the described technique, with FAME. The stars of interest are the same ones to be used in the study of $H_2$ listed above.

The masses of known clouds clearly depend on the actual distance to the clouds from Earth, which distances can be determined by FAME. Large-scale features, such as Radio Loop I, that appear to be the result of massive flows of interstellar material, cannot be analyzed without knowing the gas masses. Having the masses, one can calculate the amount of energy required to create the features and thus decide what caused the ordering of the gas. The Orion Cloak study, mentioned above, as well as the MBM cloud studies, need to be redone with this calculation in mind.

The required precision in the distances is not as high as for the radiation field problems described earlier, but parallax errors better than 200 μas will be needed to get accurate masses and densities for the problems listed.

## 3.7.4 Distances to Detached Eclipsing Binaries

Ground-based photometric surveys are turning up large numbers of detached eclipsing binaries (DEBs) in the Large and Small Magellanic Clouds (LMC and SMC). If double-lined spectroscopic orbits can be obtained, the distances to these binaries can be derived directly. The accuracy of this distance determination technique can be checked using FAME distances to about 50 bright ($V < 10$ mag) nearby DEBs in the Galaxy. The set of DEBs to be studied by FAME will include early type stars (mostly B-type) to be used in calibrating the distance to the SMC and LMC, as well as later type stars (A-G) to be used in calibrating distances to globular clusters.

### 3.7.5 Galactic Kinematics

Many problems in Galactic kinematics can be solved using the FAME proper-motion data. For example, a mapping of the asymmetric drift velocity (the velocity by which the halo lags behind the rotation of the disk around the Galactic center) as a function of height in the halo can be determined directly, without the need to have radial velocity information, by observing the distribution of proper motions at the galactic pole (where one gets both the U and V velocities if one also knows the distances).

Up to a distance of 1000 pc, where FAME will deliver parallaxes better than $\delta\pi/\pi=0.05$ for stars brighter than $V=9$ mag, velocities of 100 km/s translate into the proper motions of 20 mas/yr, well above the FAME limit. Hence, the asymmetric drift, which is about 220 km/sec for Population II field stars, can be mapped as a function of both the V velocity and of the height above the plane using direct parallaxes to 1000 pc and photometric parallaxes to 8000 pc, for stars such as RR Lyraes and blue horizontal branch stars at $M_V=0.5$ mag. At 8000 pc a drift velocity of 220 km/sec has a proper motion of 6 mas/yr, which is more than 10 times above the FAME error of 500 µas/yr at $V=15$ mag. Hence, the method is exceedingly powerful even at $V=15$ mag.

### 3.7.6 Galactic Evolution

The FAME catalog will provide a superb resource for modeling the spatial distribution, kinematics, chemical compositions, and in some cases even ages of Galactic stars. In addition to positions, proper motions, and parallax measurements, the catalog will provide photometric results with several astrophysical filters suitable for deriving effective temperatures, surface gravities, metallicities, and in some cases ages. These data will be sufficient to test and revise existing models of the distribution of Galactic stars, making possible the construction of models that include the number densities of stars of different types in different volumes of the Galaxy. The results from the astrophysical filters will enable comparisons of the kinematics, metallicities, and ages of various populations, which will lead to a better understanding of the formation and evolution of the galaxy, and the history of its chemical enrichment.

## 3.8 Relativity

One of the few feasible tests of General Relativity is the predicted deflection of the path of light waves by mass. This test provides a measure of the curvature of space-time through an estimate of the metric parameter $\gamma$. The most accurate such tests so far performed involved the deflection of the path of microwaves by the Sun. The prediction of General Relativity was found to be correct to within the estimated uncertainty of about 0.02%.

No one knows at what level of accuracy General Relativity will break down. We can be sure only that at some level it will eventually break down. Although we do not expect that General Relativity will be found wanting at the level of accuracy achievable with FAME, nonetheless, the analysis should be carried out, if for no other reason than to check the results for the microwave experiments. The sources of systematic error in these two approaches are very different. A crude error analysis indicates that a 1-$\sigma$ uncertainty in the estimate of $\gamma$ from FAME measurements might be as small as 0.005%. This result depends on many assumptions, including a 45 deg minimum value for the angular separation of the Sun from each target star, a single measurement uncertainty in stellar position of 1 mas at $V=9$ mag, no correlation between the estimate of $\gamma$ and those of the other unknown parameters of our model, and a mission duration of 2½ years.

## 3.9 Solar System

Observations of solar system objects at µas levels, while interesting and of unprecedented accuracy, generally have limited scientific interest. The determination of improved ephemerides requires observations over a more extensive time period than the duration of the FAME mission. There are a few cases where the observations may be of significance scientifically. One is the determination of masses of asteroids. This is one of the largest sources of uncertainty in solar system ephemerides. Very precise observations of asteroids over the period that they are experiencing perturbations by each other could lead to more accurate determinations of the masses of the perturbing asteroids. This will require a careful selection of the asteroids, determinations of the optimum times for making the observations, and special inclusion of predicted asteroid positions in the input catalog. The accuracy achievable depends on the circumstances of the specific encounters.

There is also the possibility of observing long-period comets to determine the mass of the Kuiper Belt. This will require the selection of appropriate comets and observations over the duration of the FAME mission.

## 3.10 Photometry

To achieve the astrometric performance required of FAME, the color of each star must be known to better than 0.1 mag at the time of each observation, so that the point-spread function can be modeled with sufficient accuracy. More accurate color information, say to the level of 0.01 mag, may prove to be very useful in the analysis of systematic errors. Because the necessary color information is not available for the majority of the FAME target stars, FAME itself will be used to obtain the necessary photometric observations.

In addition, photometry with FAME will allow the identification of variable stars at an unprecedented level of sensitivity. The photometric precision will allow the identification of variables with amplitudes of about 10 mmag , and the number of observations (~1000 or more in the astrometric band-pass) will allow the identification of stars with infrequent changes such as stars undergoing flares and/or eclipses or transits. The observing window function will prevent complete characterization of the variability for many stars (those with multiple periods, for example), but just their identification will allow ground-based follow-up studies.

Photometry with the g', r', i', and z' SDSS filters (York et al. 2000) together with the FAME astrophysical filters will allow constraints to be placed on the astrophysical parameters of most stars, primarily effective temperature, surface gravity, metallicity, reddening, extinction, and in some cases even age. With the baseline photometric accuracy required for the mission, the mean magnitudes of stars will be measured with an accuracy better than 1 mmag at $V$=9 mag and 10 mmag at $V$=15 mag. This accuracy is better than is normally attained in ground-based all-sky photometry.

### 3.10.1 Statistical Parallax of RR Lyraes

The FAME statistical parallax calibration of RR Lyraes will be based on a sample of approximately 750 stars with $V$<13 mag. For a large fraction of these, only photographic photometry is presently available which, as Gould & Popowski (1998) showed, is sometimes plagued by severe systematic errors. Hence, obtaining CCD photometry for these stars is critically important. If the photometric errors are truly random, even 0.05 mag errors would be quite adequate.

A somewhat more stringent requirement comes from wanting to obtain accurate ephemerides, which in turn are needed so that one can measure the systemic radial velocities from a single (ground-based) spectroscopic observation. (The alternative is to obtain at least 3 spectroscopic measurements, which would be a huge project for this large sample, although not prohibitive.) For this purpose, 0.05-mag photometry in the astrometric band-pass at each epoch would be adequate. Expressed as a 2½-yr mission average, this would be 0.05 mag/sqrt{N} ~ 0.002 mag, where N = 900 is the number of times FAME returns to the same star.

A similar level of photometry is needed to find new RR Lyraes from their light curves, since a non-negligible minority of RR Lyraes at $V$=13 mag remain undiscovered.

### 3.10.2 Subdwarf Distance Scale

The subdwarf distance scale will be determined from about 200 subdwarfs. The majority will be near the magnitude limit of the subdwarf surveys, $V$=12-14 mag. In order to relate the parallaxes of FAME subdwarfs to those of comparable stars on the main-sequences of globular clusters, each subdwarf must be assigned an accurate metallicity, temperature, reddening, and extinction, which in turn requires a variety of photometric and spectroscopic observations. This information is already available for many of the known subdwarfs (Carney et al. 1994). For subdwarfs newly discovered by FAME, the needed optical photometry will be obtained by FAME itself. A photometric accuracy of about 0.01 mag is needed, which is equal to the FAME goal at $V$=12 mag. It should be pointed out that if FAME falls short of this goal, then the needed photometry and supplementary spectroscopy can be obtained from the ground.

### 3.10.3 Standard Candles

Accurate mean magnitudes in the SDSS filters will be obtained for Cepheids, RR Lyraes, non-variable horizontal branch stars, stars in open clusters, and main-sequence metal-poor subdwarfs. Together with the astrometry, these magnitudes and colors will be particularly useful for confirming the Cepheids that are members of open clusters and for improving their reddening and extinction determinations. The FAME photometric accuracy will be better than necessary for most of these purposes.

### 3.10.4 Brown Dwarfs and Planets

A transit of a solar-type star by a Jupiter-sized planet (or a brown dwarf star) results in a dimming of the primary star by about 10 mmag. A transit of a lower mass star having a smaller radius gives a greater variation. Measurements of transits can be used to determine the radius and density of a planetary companion if a spectroscopic orbit is available.

FAME's required photometric accuracy in the astrometric bandpass for individual measurements (3 mmag for $V$=9 mag, 12 mmag for $V$=12) is sufficient to allow FAME to search for transits by substellar to sub-Jupiter companions. Typical planetary transits last on the order of a few hours. FAME will observe each star typically 6 times during two consecutive scans lasting 1 hour (and often more during additional scans), and this pattern will be repeated at 10-day intervals. This coverage can catch at least a portion of one or more planetary transits for those planetary systems with high inclinations and relatively short periods. Given the large number of stars on the main sequence observed by FAME (roughly a million stars to $V$=12 mag), many planetary systems will be detected photometrically. A degradation of the photometric accuracy to 10 mmag will still be useful for detecting those transits with relatively large amplitudes, like the transits of HD 209458.

### 3.10.5 Variability of Solar-type Stars

FAME can detect Sun-like variability in ~40,000 Sun-like main-sequence stars to $V$=10 mag with its baseline photometric accuracy. The Sun shows significant photometric variations on timescales from minutes to decades, dimming by as much 0.2% when large sunspot groups transit the solar disk, brightening by 0.1-0.2% with the 11-yr solar cycle, and perhaps dimming by 0.2-0.6% during the Maunder minimum periods (e.g. 1645-1715) of extended inactivity.

Main-sequence stars below 1.5 solar masses have convection zones, and thus may have magnetic activity cycles similar to the Sun's. Previous studies of small samples (less than 100) of solar-like G and K stars show that variability at the 0.5% level or larger is common (~40%, e.g. Radick et al. 1998). These stars, more variable than the Sun, can be studied to $V$=12 mag with FAME's baseline photometric accuracy, increasing the present sample by an enormous factor. With distances of a few hundred pc, all these stars will have FAME parallaxes to locate them on or above the main sequence. Both younger and older solar-like stars appear to organize their surface magnetic activity into active regions broadly similar to those seen on the Sun; young, active stars may have spot-dominated variability (with flux deficits), in contrast to the faculae-dominated activity (with flux excesses) of older stars, including the Sun (Radick et al. 1998). A statistical study of stellar cycles can give insight into the production of magnetic dynamos and shed light on the incidence of Maunder-minimum-like behavior in stars. It might also identify otherwise solar-like stars less likely to have planets harboring life as we know it due to conditions of extreme variability. The photometric signature of star spots on a rotating star are very different from that of a planetary transit, so it should be possible to distinguish between these two effects.

With the FAME baseline accuracy (3 mmag at $V$=10 mag for 1 observation) and typically 6 observations each 10-day semi-precession period, 0.1% variations can be studied for brighter stars on timescales of months or longer, and 0.2% variations at $V$=12 mag. Yearly variations will be detectable to levels more sensitive by a factor of about four. The photometric filters will give very good mean colors, and (with parallaxes) locate the stars accurately in the color-magnitude diagram. Coverage will be more continuous for a fraction of stars for which the ecliptic latitude is just greater than the Sun angle; this set can be used to look for ~0.1% variations for $V$=10 mag stars. A photometric accuracy degraded to 20 mmag for a single observation would give 1 mmag yearly accuracy, and would still detect cyclic variations of some of the more variable solar analogs.

### 3.10.6 Stellar Pulsation

Evolved stars in the upper instability strip with radial pulsations (SX Phe, RR Lyr, Type II Cepheids, and RV Tau stars) have large amplitudes; they will all be identified, and their periods and light curves measured. Variable light curves (e.g., stars with double modes, RR Lyrae with the Blazhko effect, and RV Tau stars) will be easily identified for bright stars, even with the photometric accuracy degraded to 30 mmag per observation. When combined with parallax data and colors from FAME, the boundaries of the instability strip will be accurately defined for SX Phe and RR Lyr stars (several hundred stars each), and short-period Type II Cepheids. Parallaxes for the dozen or two long-period Cepheids and RV Tau stars that are nearby enough will define the period-luminosity-color relation(s) for all these low-mass stars much more accurately than now.

The identification of low-amplitude non-radial pulsators near the main sequence ($\delta$ Sct, $\lambda$ Boo, and rotating Ap stars) in order to define the instability strip for these stars requires a photometric accuracy better than 10 mmag per observation. This accuracy will be reached for $V$<12 mag with the FAME baseline accuracy, and will still be useful if reached at $V$=9-10 mag.

### 3.11 References

Butler, R.P., Marcy, G.W., Fischer, D.A., Brown, T.M., Contos, A.R., Korzennik, S.G., Nisenson, P., & Noyes, R.W., 1999, ApJ, 526, 916.

Carney, B.W., Latham, D.W., Laird, J.B., & Aguilar, L.A., 1994, AJ, 107, 2240.

Charbonneau, D., Brown, T.M., Latham, D.W., & Mayor, M., 2000, ApJ, 529, L45.

Cowie, L.L., Songaila, A., & York, D.G., 1979, ApJ, 230, 469.

Demarque, P., Guenther, D.B., & Kim. Y-C., 1999, ApJ, 517, 510.

Dean, J.F., Warner, P.R., & Cousins, A.W.J., 1978, MNRAS, 183, 569.

Douglas, A.E., 1977, Nature, 269, 130.

Feast, M. & Catchpole, R., 1997, MNRAS, 286, L1.

Feast, M. & Whitelock, P., 1997, MNRAS 291, 683.

Fernie, J.D., 1990, ApJ, 354, 295.

Frisch, P.F., Sembach, K., & York, D.G., 1990, ApJ, 364, 540-548.

Frisch, P.C., & York, D.G., 1983, ApJ, 271, L59-L63.

Geballe, T.R., McCall, B.J., Hinkle, K.H., & Oka, T., 1999, ApJ, 510, 251, 1999.

Gould, A. & Popowski, P., 1998, ApJ, 508, 844.

Henry, G.W., Marcy, G.W., Butler, R.P., Vogt, S.S., 2000, ApJ, 529, L41.

Knude, J. & Høg, E., 1998, A&A, 338, 897.

Laney, C.D. & Stobie, R.S., 1994, MNRAS, 266, 441.

Lattanzi, M.G., Spagna, A., Sozzetti, A., & Casertano, S., 2000, MNRAS, 317, 211.

Lepp, S., Dalgarno, A., van Dishoeck, E.F. & Black, J.H., 1988, ApJ, 329, 418.

Lutz, T.E. & Kelker, D.H. 1973, PASP, 85, 573.

Magnani, L., Blitz, L. & Mundy, L., 1985, ApJ, 205, 402.

Mazeh, T., Goldberg, D., & Latham, D.W. 1998, ApJL, 501, L199.

McCall, B.J., Geballe, T.R., Hinkle, K.H. and Oka, T., 1998, Science, 279, 1910.

Morton, D.C., 1978, ApJ, 222, 863.

Narayanan, V. & Gould, A., 1999a, ApJ, 515, 256.

Narayanan, V. & Gould, A., 1999b, ApJ, 523, 633.

Newberg, H.G., Richards, G.T., Richmond, M., and Fan, X., 1999, ApJ Suppl, 123, 377.

Pinsonneault, M.H., Stauffer, J., Soderblom, D.R., King, J.R., Hanson, R.B., 1998, ApJ, 504, 170.

Radick, R.R., Lockwood, G.W., Skiff, B.A., & Baliunas, S.L., 1998, ApJS, 118, 239.

Rachford, B.L., Snow, T.P., Tumlinson, J., Shull, J.M., Andre, M., Dessert, J.M., Ferlet, R., Vidal-Madjar, A., Roueff, E., & York, D. G., 2001, astroph 2001.

Seidensticker, K.J. & Schmidt-Kaler, T., 1989, A&A, 225, 192.

Smith, W.H., Snow, T.P. & York, D. G., 1977, ApJ, 218, 124.

Snow, T.P., Rachford, B.L, Tumlinson, J., Shull, J.M., Welty, D.E., Blair, W.P., Ferlet, R., Friedman, S.D., Gry, C., Jenkins, E.B., Morton, D.C., Savage, B.D., Sembach, K.R., Vidal-Madjar, A., York, D.G. and the FUSE Science Team, 2000, ApJL, 538, L65.

Spitzer, L. & Cochran, W.D., 1973, ApJL, 186, L23.

Talbot, T.J. & Newman, M. J., 1977, ApJS, 34, 295.

Welty, D.E., Hobbs, L.M., Lauroesch, J.T., Morton, D.C., Spitzer, L., & York, D.G.,1999, ApJS**,** 124, 465.

Welty, D. E., Hobbs, L. M., Penprase, B. E. & Blitz, L. 1989, ApJ, 346, 232.

Welty, D.E., Frisch, P.C., Sonneborn, G. & York, D.G., 1999, ApJ, 512, 636.

York, D., et al., 2000, AJ, 120, 1579.

### 3.12 Definitions

| | |
|---|---|
| DEB | Detached Eclipsing Binary |
| FAME | Full-sky Astrometric Mapping Explorer |
| GMC | Giant Molecular Cloud |
| HR | Hertzsprung-Russell Diagram |
| IAU | International Astronomical Union |
| ICRF | International Celestial Reference Frame |
| ICRS | International Celestial Reference System |
| LMC | Large Magellanic Cloud |
| mas | milliarcseconds |
| $M_J$ | Mass of Jupiter |
| mmag | millimagnitude |
| $M_V$ | Absolute Magnitude in the Johnson *V* filter |
| pc | parsec |
| PMS | Pre-Main-Sequence |
| PNe | Planetary Nebulae |
| sd | Subdwarf |
| SDSS | Sloan Digital Sky Survey |
| SFR | Star-Forming Region |
| SIM | Space Interferometry Mission |
| SMC | Small Magellanic Cloud |
| TPF | Terrestrial Planet Finder |
| μas | microarcseconds |
| *V* | Apparent visual magnitude in the Johnson *V* filter |
| VLBI | Very Long Baseline Interferometry |
| WD | White Dwarf |